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JOHN E. GREENLEAF, BRUCE L. CASTLE, AND DON H. CARD

# BLOOD ELECTROLYTES AND TEMPERATURE REGULATION DURING EXERCISE IN MAN*

Laboratory of Human Environmental Physiology, Human Studies Branch, NASA — Ames Research Center Moffett Field, California 94035

*Greenleaf, J. E., Castle, B. L.* and *Card, D. H.:* Blood electrolytes and temperature regulation during exercise in man. Acta Physiol. Pol. 1974, 25 (5): 397—410. To determine if changes in blood osmotic and electrolyte concentrations influence body temperature regulation, rectal ($T_{re}$), auditory canal ($T_{ac}$), and mean skin temperatures ($\bar{T}_{sk}$), sweat rates ($m_{sw}$), and tissue conductances (K) were measured in 8 men (21—27 years) who exercised on a bicycle ergometer for 70 minutes ($T_{db}$ = 23.6°C, rh = 50%) at 49% of their maximal oxygen uptake under three levels of hydration. Serum electrolyte and osmotic concentrations were increased by dehydration (Δ body wt = −5.2%) and decreased by excessive water consumption (body wt = + 1.2%); a normal hydration control experiment was also performed (body wt = −1.6%). Equilibrium levels of $T_{re}$ were linearly related to the level of hydration; $T_{re}$ changed 0.1°C for each 1% change in body water (wt). Equilibrium levels of $\bar{T}_{sk}$ and $\Delta\bar{T}_{sk}$ were constant and independent of Δ body water between +1.2 and −5.2%. Hypohydration HR and $\dot{V}_{O_2}$ were increased and equilibrium levels of $\dot{V}_{EBTPS}$, $\bar{T}_{sk}$, respiratory water loss, and tissue conductance were unchanged. Sweating and evaporative heat loss were reduced. Between 77 and 100% of the excessive rise in body temperature could be accounted for by reduction in sweating. At equilibrium, during exercise the correlation between $T_{re}$ and plasma volume was r = 0.04 (N. S.); $T_{re}$ and serum Na, r = 0.71 ($p<0.05$). At equilibrium $T_{re}$ also correlated significantly with serum chloride, blood pH, respiratory rate, and heart rate while sweat rate was related only to $T_{sk}$ (r = −0.57, $p<0.05$).

The mechanism for the precise control of temperature regulation during exercise is not completely understood. From the work of *Nielsen* [35] it is known that the rise in core temperature during exertion is a regulated process and not the result of failure of the heat-dissipating mechanism.

* A preliminary report of these data was presented at the Symposium on the Pharmacology of Thermoregulation, San Francisco, 1972, and at the American Physiological Society Meeting at Pennsylvania State, August 1972.

Regulatory sweating appears to be a linear function of skin and core temperatures when exercise is performed continuously in the upright position and equilibrium temperature conditions are attained. The failure of changes in skin and core temperatures to account for the rate of sweating during intermittent exercise [13, 16], during work in the supine position [16], at altitude [18], and during negative work — walking downhill [41] suggests that factors other than skin and core temperatures are important in the mechanism controlling sweating.

The afferent stimuli for controlling sweating have not been fully defined. Many hypotheses have been suggested for the control of exercise sweating [2—6, 14, 20, 21, 33], but no satisfactory mechanism has been found that takes into consideration a local stimulus for sweating associated with skin temperature, a central stimulus for sweating associated with core temperature, and the simultaneous control of heat flow to the skin via changes in peripheral blood flow.

It is probable that variations in blood osmotic and electrolyte content play significant roles in the control of body temperature regulation. *Myers* and *Yaksh* [32] and *Myers* and *Veale* [31] have shown that direct injection of sodium and calcium ions into cerebral ventricles of resting monkeys and cats changes body temperature. Furthermore, increased serum osmolarity and sodium concentrations are associated with decreased sweating during rest and exercise in the heat [16, 38], and peripheral blood flow can be altered by different blood osmotic and potassium levels [29, 40].

The purpose of this study was to investigate the effect of changes in blood osmotic and electrolyte concentrations on temperature regulation during exercise.

## MATERIAL AND METHODS

Body temperatures, heat production, heat loss, and various blood constituents were measured in eight healthy university students during 70 minutes of moderate exercise at three levels of hydration (Table 1).

Prior to the hydration experiments, maximal oxygen uptake was determined with the subjects working on a bicycle ergometer [7]. The subjects then underwent three 2-hour conditioning exposures to 43°C (110°F) dry-bulb temperature ($T_{db}$) with one day of rest between exposures. They worked at a load that resulted in a relative oxygen uptake ($\dot{V}_{O_2} \times 100/\dot{V}_{O_2}$ max) of 28%. One to two weeks later the hydration experiments were begun; the subjects worked for 70 minutes in the upright position on the ergometer at an average relative $\dot{V}_{O_2}$ of 49%. The use of similar relative $\dot{V}_{O_2}$ levels reduces interindividual variability in equilibrium levels of core temperatures during exercise [18]. Each subject underwent three pre-exercise treatments selected in random order; dehydration,

*Table 1.* Baseline anthropometric, blood volume, and maximal exercise data on the subjects; the workload was that used in the three hydration experiments

| Subject | Age, yr | Height, cm | Weight, kg | $A_b$, $m^2$ | $\dot{V}_{O_2}$ max, liters/min | $\dot{V}_{E\,BTPS}$ max, liters/min | Heart rate max, beats/min | Blood volume, liters | Hct vol% | Workload, kpm/min |
|---|---|---|---|---|---|---|---|---|---|---|
| AMB | 21 | 181 | 80.92 | 2.01 | 4.38 | 185.02 | 198 | 5.98 | 44.2 | 888 |
| BUC | 22 | 179 | 90.98 | 2.10 | 5.97 | 201.04 | 198 | 6.75 | 45.7 | 1163 |
| DUF | 21 | 173 | 75.00 | 1.89 | 4.66 | 132.40 | 192 | 5.64 | 45.3 | 980 |
| GIL | 21 | 198 | 88.28 | 2.23 | 5.34 | 154.06 | 189 | 7.30 | 43.2 | 1133 |
| JEW | 27 | 186 | 66.82 | 1.89 | 2.83 | 117.65 | 201 | 6.08 | 41.8 | 551 |
| McC | 26 | 186 | 93.06 | 2.18 | 3.93 | 168.78 | 204 | 6.23 | 45.8 | 796 |
| SCH | 23 | 188 | 79.14 | 2.05 | 5.08 | 198.65 | 183 | 7.14 | 45.4 | 1102 |
| SHA | 24 | 180 | 66.66 | 1.85 | 4.23 | 140.44 | 177 | 6.05 | 41.4 | 888 |
| $\bar{X}$ | 23 | 184 | 80.11 | 2.02 | 4.55 | 162.26 | 193 | 6.40 | 44.1 | 938 |
| ± S.E. | 1 | 3 | 3.63 | 0.05 | 0.34 | 11.03 | 3 | 0.21 | 0.6 | 72 |

normal hydration, and hyperhydration. (The term dehydration is used when the body is undergoing negative water balance; hypohydration is used when the body is in water balance but the total volume of water is reduced). The subjects were dehydrated the evening before the experiment by alternating rest with moderate work at 43°C (110°F) until their body weight was decreased by 5%. A similar heat exposure was given prior to the normal hydration and hyperhydration experiments, except the subjects were required to drink water equal to their weight losses. They retired in the laboratory. Before exercise the next morning, the hypohydrated subjects drank nothing; with normal hydration they drank 100—200 ml of tap water; with hyperhydration they consumed about 40 ml/kg (2.5—3,0 liters) of tap water (37°C) the hour before exercising. The subjects ate no breakfast. During exercise with normal hydration and hypohydration, the subjects drank 0.9% saline (37°) intermittently to equal their body weight loss; with hyperhydration they consumed tap water (37°C). Because of their sudorific effect, tap water and saline were administered at 10-minute intervals. The purpose for the variation in tonicity of the drinking fluid administered during exercise was to hold the serum sodium and osmotic concentrations (and the plasma volume) the same as the resting levels that were altered by the various hydration procedures.

Heart rate was counted from an ECG record and oxygen uptake was determined with standard techniques [16]. The levels of dehydration and hyperhydration were determined from body weight changes between the evening weight before heat exposure and the morning preexercise weight. Sweat rate ($\dot{m}_{sw}$) was calculated as:

$$\dot{m}_{sw} = \left[\begin{array}{l}\text{total body} \\ \text{weight loss} - \dot{m}_{ex} - (118.6\ \dot{V}_{CO_2} - 85.7\ \dot{V}_{O_2})\end{array}\right] \quad \text{in grams per hour}$$

where $\dot{V}_{CO_2}$ is expired $CO_2$ in liters/min, $\dot{V}_{O_2}$ is expired $O_2$ in liters/min, and $\dot{m}_{ex}$ is expired water loss in g/h; $\dot{m}_{ex} = V_{E_{BTPS}} (P_{ex} - \varnothing_a P_a)$ in g/h, where the 175-ml dead space in the respiratory value was accounted for the calculation of $V_{E_{BTPS}}$; $P_{ex}$ is the density of expired gas at 34°C (in kg/m³), $\varnothing_a$ is the humidity of the ambient air at 24°C and $P_a$ is the density of the ambient air (in kg/m³). Body weight was measured before exercise, at 35 minutes during exercise, and at the end of exercise. Efficiency was calculated as:

Efficiency = (kpm/min × 100) [426.85 kpm/kcal (total kcal/min-basal kcal/min)].

Total metabolic heat production ($M_{gross}$) was calculated from the $O_2$ uptake. The heat available for dissipation ($M_{net}$) equals $M_{gross}$ minus the heat loss due to the external work, calculated from the work efficiency.

Evaporative heat loss ($E_s$) and respiratory heat loss ($E_r$) were calculated by multiplying sweat and respiratory water losses by 0.58 kcal/g. Tissue conductance (K) was calculated from:

$$K = (M_{net} - E_r)\ (T_{re70} - \overline{T}_{sk70})$$

Mean body temperature $(\overline{T}_{mb}) = 0.8\,T_{re} + 0.2\,\overline{T}_{sk}$

Body temperatures were measured with individually calibrated YSI thermistors (400 series) with an accuracy of ±0.05°C. The rectal thermistor was inserted 17 cm. The auditory canal thermistor was held in place with a customifitted hearing-aid ear mold and the thermistor tip was located about 10 mm from the tympanic membrane [17]. The six skin thermistors, attached to spring clips connected to plastic rings, allowed sweat to evaporate freely. Mean skin temperature ($\overline{T}_{sk}$) was calculated as (0.06 arm

temperature + 0.13 forearm and hand + 0.09 chest + 0.20 back + 0.21 thigh + 0.21 leg and foot). Average ranges of environmental parameters were: globe temperature 23.9° to 24.0°C; $T_{db}$ 23.5° to 23.7°C; $T_{wb}$ 16.7° to 16.8°C; rh 50 to 52%; $P_{H_2O}$ 10.7 to 10.9 mmHg, and barometric pressure 764.3 to 765.0 mmHg. Turbulent air flow averaged 0.41 m/sec (80 ft/min).

Venous blood samples were taken without stasis before exercises, at 35 minutes, and just after exercise. Blood volume was determined just prior to exercise (0 minute) from one 10-minute postinjection sample utilizing radio-iodinated (I-131) human serum albumin (Miles Lab.) with the method of [42]. At 0 minute, plasma volume (PV) was calculated as: PV = blood vol 1-Hct (0.96×0.91) where 0.96 is the correction for trapped plasma and 0.91 is the correction for the total body Hct/venous Hct ratio [39]. Plasma volume at 35 minutes and after exercise was calculated from the 0-minute PV and Hct (pre) and the 35-minute Hct (post) and post-exercise Hct (post) from the following formula (4):

$$PV_{post} = \left\{ \frac{[PV_{pre}/1 - (Hct_{pre} \times 10^{-2})] - PV_{pre}}{Hct_{post} \times 10^{-2}} \right\} - \left\{ [PV_{pre}/1 - (Hct_{pre} \times 10^{-2})] - PV_{pre} \right\}$$

In a separate study on seven men, a comparison was made between PV extrapolated to injection time from 10, 20, 30, and 60-minute postinjection samples and the 10-minute sample. The mean (±SE) PV for the extrapolated data was 3,347±177 ml; the average (±SE) percentage difference in PV between the two methods was 0.5±0.3% [43]. Blood for hematocrit determinations was drawn in triplicate into capillary tubes and spun for 12 minutes at 11,500 rpm in a Model MB International centrifuge and read on an International microcapillary tube reader. Only measurements with 0.1% or less variation in the hematocrit ratio were accepted. Serum osmolarity was measured by freezing point depression (Fiske osmometer). Serum Na and K concentrations were determined by atomic absorption (Perin Elmer Model 303), serum Cl by titration [9], and blood pH by the Astrup technique. Total plasma protein was determined colorimetrically [10] and plasma albumin was measured with the Beckman Microzone system [27].

The statistical analyses were determined with the UCLA Biomedical Computer Programs [11] and run on an IBM 7090 computer.

## RESULTS

Rectal ($T_{re}$), auditory canal ($T_{ac}$), and mean skin ($\bar{T}_{sk}$) temperatures, during rest and the 70-minute exercise period are presented in Figure 1. At rest (0 minute), hypohydration $T_{re}$ was 0.2° to 0.3° higher ($p < 0.01$) than normal- or hyperhydration values. After the third minute, hypohydration $T_{re}$ was significantly higher ($p < 0.025$) than hyperhydration $T_{re}$, and the three $T_{re}$ levels were all different from each other ($p < 0.001$) from minute 10 to the and of exercise. There was no significant difference in the three $T_{ac}$ or the three $T_{sk}$ temperature curves during rest or exercise (Fig. 1, Table 2), but auditory temperatures showed a separation similar to $T_{re}$ at the three hydration levels. Average (±SE) equilibrium levels of oxygen uptake increased slightly with decreasing levels of hy-

dration: 2.08±0.10 liters/min for hyperhydration, 2.11±0.12 liters/min for normal hydration, and 2.21±0.13 liters/min for hypohydration. The average relative oxygen uptakes were not different, but oxygen uptake expressed as ml/(min · kg) was elevated ($p < 0.01$) with hypohydration (Table 2). With decreased hydration, average sweat loss progressively

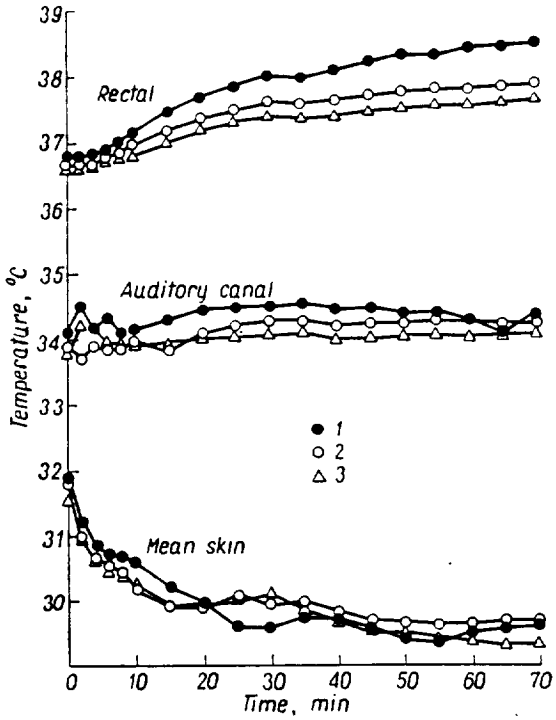


*Fig. 1.* Average (±S.E.) rectal, auditory canal, and mean skin temperatures at rest (0 minute) and during 70-minute exercise under three hydration regimes. Hypohydration $T_{re_0}$, $T_{re_{70}}$, and $\Delta T_{re}$ were higher ($p < 0.01$) than hyperhydration values; $T_{ac_0}$, $T_{ac_{70}}$, $\Delta T_{ac}$, $\overline{T}_{sk_0}$, $\Delta\overline{T}_{sk_{70}}$, and $\overline{T}_{sk}$ were not significantly different. *1* — Hypohydration; *2* — Normalhydration; *3* — Hyperhydration.

decreased (N.S.), respiratory water loss and tissue conductance (peripheral blood flow) were constant, and net metabolic heat production (heat available for dissipation) increased slightly (N.S.) (Table 2). Average heart rates increased progressively with increasing levels of dehydration. During hypohydration both resting and exercise heart rates were higher ($p < 0.005$) than those during hyperhydration.

The statistical analyses of plasma volumes, hematocrit, pH, and electrolyte concentrations at rest and during exercise are presented in Table 3. Serum osmolarity and sodium and chloride concentrations were held relatively constant. Serum potassium and blood pH reached equilibrium

*Table 2.* Average oxygen uptake, body temperature, water loss and heat exchange during exercise under three levels of hydration. (See title of Table 3.)

$\dot{V}_{O_2} \times 100$ Respira-

*Table 2.* Average oxygen uptake, body temperature, water loss and heat exchange during exercise under three levels of hydration. (See title of Table 3.)

| Subject | $\dot{V}_{O_{2_{60}}}$ ml/(min·kg) | $\frac{\dot{V}_{O_2} \times 100}{\dot{V}_{O_2}\ MAX}$ % | $T_{re_{70}}$ °C | $\Delta T_{re}$ °C | $\bar{T}_{sk_{70}}$ °C | $\Delta \bar{T}_{sk}$ °C | $\bar{T}_{mb_{70}}$ °C | $\Delta \bar{T}_{mb}$ °C | Sweat loss g/(m²·h) | Respiratory $H_2O$ loss g/(m²·h) | Tissue Conductance kcal/(m²·h·°C) | Efficiency % | $M_{gross}$ kcal/(m²·h) | $M_{net}$ kcal/(m²·h) | $E_s$ kcal/(m²·h) | $E_r$ kcal/(m²·h) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **1. Hyperhydration** | | | | | | | | | | | | | | | | |
| AMB | 24.8 | 47.5 | 37.70 | 0.80 | 28.63 | —3.55 | 35.89 | —0.07 | 174 | 30 | 22.8 | 23.9 | 296 | 225 | 101 | 18 |
| BUC | 26.4 | 43.7 | 37.65 | 0.92 | 28.82 | —1.97 | 35.88 | 0.34 | 210 | 41 | 27.9 | 24.1 | 356 | 270 | 122 | 24 |
| DUF | 26.5 | 45.1 | 37.53 | 0.94 | 29.18 | —1.86 | 35.86 | 0.38 | 202 | 35 | 25.9 | 26.1 | 319 | 236 | 117 | 20 |
| GIL | 25.0 | 48.1 | 37.92 | 1.09 | 29.51 | —2.48 | 36.24 | 0.38 | 157 | 35 | 26.2 | 24.0 | 328 | 250 | 91 | 20 |
| JEW | 22.5 | 51.2 | 37.51 | 0.92 | 30.39 | —1.18 | 36.09 | 0.51 | 26 | 33 | 21.5 | 22.4 | 222 | 172 | 15 | 19 |
| McC | 20.9 | 52.4 | 37.53 | 0.86 | 29.21 | —2.33 | 35.86 | 0.21 | 173 | 35 | 23.2 | 21.6 | 271 | 213 | 100 | 20 |
| SCH | 28.2 | 45.7 | 37.61 | 0.88 | 29.58 | —2.68 | 36.01 | 0.18 | 204 | 37 | 26.5 | 26.4 | 319 | 235 | 119 | 22 |
| SHA | 29.8 | 47.3 | 37.65 | 1.97 | 29.35 | —1.87 | 35.99 | 1.21 | 139 | 33 | 25.3 | 25.2 | 307 | 229 | 77 | 19 |
| $\bar{x}$ | 25.5 | 47.6 | 37.64 | 1.05 | 29.33 | —2.24 | 35.98 | 0.39 | 160 | 35 | 24.9 | 24.2 | 302 | 229 | 93 | 20 |
| ±SE | 1.0 | 1.0 | 0.05 | 0.14 | 0.19 | 0.25 | 0.05 | 0.13 | 21 | 1 | 0.7 | 0.6 | 14 | 10 | 12 | 1 |
| **2. Normal Hydration** | | | | | | | | | | | | | | | | |
| AMB | 25.6 | 50.0 | 37.88 | 1.29 | 28.59 | —3.77 | 36.02 | 0.28 | 168 | 34 | 22.4 | 22.3 | 317 | 247 | 98 | 20 |
| BUC | 28.7 | 44.7 | 37.84 | 1.03 | 29.41 | —2.32 | 36.15 | 0.35 | 179 | 42 | 30.4 | 23.6 | 366 | 280 | 104 | 24 |
| DUF | 27.7 | 45.1 | 37.63 | 0.82 | 30.15 | —1.16 | 36.13 | 0.42 | 221 | 33 | 29.3 | 26.0 | 322 | 238 | 128 | 19 |
| GIL | 27.9 | 49.6 | 38.13 | 1.24 | 28.75 | —2.79 | 36.25 | 0.43 | 169 | 37 | 25.8 | 23.2 | 343 | 264 | 98 | 22 |
| JEW | 22.3 | 54.4 | 37.67 | 1.19 | 31.00 | —1.33 | 36.34 | 0.69 | 55 | 30 | 25.2 | 21.1 | 235 | 186 | 32 | 18 |
| McC | 21.2 | 48.6 | 38.31 | 1.31 | 29.19 | —2.07 | 36.49 | 0.64 | 106 | 31 | 19.2 | 23.6 | 253 | 193 | 61 | 18 |
| SCH | 26.5 | 41.3 | 37.96 | 1.29 | 29.71 | —2.35 | 36.31 | 0.56 | 130 | 34 | 22.5 | 29.6 | 293 | 206 | 76 | 20 |
| SHA | 30.9 | 51.5 | 37.68 | 1.85 | 30.71 | —1.34 | 36.28 | 1.21 | 162 | 34 | 35.2 | 22.6 | 342 | 265 | 94 | 20 |
| $\bar{x}$ | 26.4 | 48.2 | 37.89 | 1.25 | 29.69 | —2.14 | 36.25 | 0.57 | 149 | 34 | 26.5 | 24.0 | 309 | 235 | 86 | 20 |
| ±SE | 1.2 | 1.5 | 0.08 | 0.10 | 0.31 | 0.31 | 0.05 | 0.10 | 18 | 1 | 1.8 | 0.9 | 16 | 13 | 10 | 1 |
| **3. Hypohydration** | | | | | | | | | | | | | | | | |
| AMB | 26.0 | 48.6 | 38.48 | 1.56 | 28.89 | | 36.56 | | 258 | 34 | 23.3 | 23.0 | 315 | 243 | 150 | 20 |
| BUC | 28.0 | 43.6 | 38.33 | 1.51 | 30.34 | —1.57 | 36.73 | 0.89 | 161 | 40 | 31.4 | 24.2 | 361 | 274 | 93 | 23 |
| DUF | 29.9 | 48.1 | 38.25 | 1.54 | 30.01 | —2.49 | 39.60 | 0.73 | 125 | 37 | 29.6 | 24.0 | 348 | 265 | 72 | 21 |
| GIL | 30.0 | 50.6 | 38.78 | 1.76 | 29.46 | —2.70 | 36.90 | 0.87 | 155 | 35 | 27.1 | 22.8 | 352 | 272 | 90 | 20 |
| JEW | 23.6 | 51.9 | 38.04 | 1.17 | 30.74 | —1.63 | 36.58 | 0.61 | 22 | 31 | 21.5 | 22.6 | 226 | 175 | 13 | 18 |
| McC | 26.7 | 59.5 | 39.17 | 2.17 | 28.42 | —2.35 | 37.02 | 1.27 | 73 | 40 | 21.2 | 19.0 | 310 | 251 | 43 | 23 |
| SCH | 31.8 | 50.4 | 38.93 | 1.89 | 30.30 | —1.65 | 37.20 | 1.18 | 128 | 46 | 29.2 | 23.5 | 365 | 279 | 74 | 27 |
| SHA | 31.7 | 49.6 | 38.15 | 1.95 | 29.02 | —2.68 | 36.32 | 1.02 | 157 | 38 | 25.6 | 23.5 | 335 | 256 | 91 | 22 |
| $\bar{x}$ | 28.5 | 50.3 | 38.51 | 1.69 | 29.65 | —2.15 | 36.74 | 0.94 | 135 | 38 | 26.1 | 22.8 | 327 | 252 | 78 | 22 |
| ±SE | 1.0 | 1.6 | 0.14 | 0.11 | 0.29 | 0.19 | 0.10 | 0.09 | 24 | 2 | 1.4 | 0.6 | 16 | 12 | 14 | 1 |
| | 0.005 (1 & 2) | N.S. | 0.001 (1)(2) (3) | 0.001 (1 & 2) (3) | N.S. | N.S. | 0.025 (1)(2) (3) | 0.005 (1 & 2) (3) | N.S. | N.S. | N.S. | N.S. | N.S. | N.S. | N.S. | N.S. |

*Table 3.* Statistical analysis of data presented in Figure 2
The numbers within the same parenthesis — (1) hyperhydration, (2) normal hydration, and (3) hypohydration — are not significantly different from each other. (1 & 2) (3) indicates (1 & 2) are not different from each other, but are significantly different from (3). N. S. means not significant at $p < 0.05$

| | 0 Minute | 35 Minutes | 70 Minutes |
|---|---|---|---|
| Serum osmolarity, mOsm/l | (1) (2) (3)<br>0.001 | (1 & 2) (3)<br>0.001 | (1) (2) (3)<br>0.001 |
| Serum sodium, mEq/l | (1) (2) (3)<br>0.001 | N. S. | (1 & 2) (3)<br>0.001 |
| Serum chloride, mEq/l | (1 & 2) (2 & 3)<br>0.025 | (1 & 2) (3)<br>0.001 | (1 & 2) (3)<br>0.001 |
| Serum potassium, mEq/l | N. S. | (1 & 2) (2 & 3)<br>0.05 | N. S. |
| Blood pH | N. S. | (1 & 2) (2 & 3)<br>0.01 | N. S. |
| Plasma protein, g/100 ml | (1 & 2) (3)<br>0.001 | (1 & 2) (3)<br>0.005 | (1 & 2) (3)<br>0.001 |
| Plasma albumin, g/100 ml | (1 & 2) (3)<br>0.005 | (1 & 2) (3)<br>0.01 | (1 & 2) (1 & 3)<br>0.005 |
| Plasma volume, liters | N. S. | N. S. | N. S. |
| Hematocrit, vol % | (1 & 2) (3)<br>0.001 | N. S. | N. S. |

levels during the last half hour of exercise. With hypohydration, the plasma volume was constant from rest to exercise while pH and potassium concentrations increased with exercise. This suggests an influx of $K^+$ and $H^+$ into the venous circulation, most likely from the exercising muscles. With hyperhydration and normal hydration, plasma volume de-

*Table 4.* Calculated and measured changes in mean body temperature for the three experiments resulting from changes in sweating and in net metabolic heat production ($M_{net}$)

| Experiment | Measured $\Delta\bar{T}_{mb}$, °C | | Calculated $\Delta\bar{T}_{mb}$, °C | |
|---|---|---|---|---|
| | $\Delta\bar{T}_{mb}$ | $\Delta\bar{T}_{mb70}$ | Sweat | $M_{net}$ |
| Hyper vs. normal | 0.18 | 0.27 | 0.19 | 0.18 |
| Normal vs. hypo | 0.37 | 0.49 | 0.25 | 0.52 |
| Hyper vs. hypo | 0.55 | 0.76 | 0.44 | 0.70 |

Mean body temperature was calculated as $(0.8\ T_{re} + 0.2\ \bar{T}_{sk})$; $\Delta\bar{T}_{mb}$ was the difference between the 70-minute value ($\bar{T}_{mb70}$) and the 0-minute value. Calculated $\Delta\bar{T}_{mb}$ from sweating was obtained from: $0.58\ (\Delta\dot{m}_{sw}) \times$ surface area $(m^2)/(0.83 \times 80.11$ kg); where $(\Delta\dot{m}_{sw}) = \Delta$ sweat loss in $g/(m^2 \cdot hr)$. Calculated $\Delta\bar{T}_{mb}$ from $M_{net}$ was obtained from: $(\Delta M) \times 2.02\ m^2/(0.83 \times 80.11$ kg); where $(\Delta M) = \Delta M_{net}$ in $kcal/(m^2 \cdot hr)$.

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creased 250 ml (7.0%) and 140 ml (3.6 %), respectively, from resting values and increased toward resting values by the end of exercise. These results suggest plasma volume decreases with exercise only in hydrated or hyperhydrated subjects.

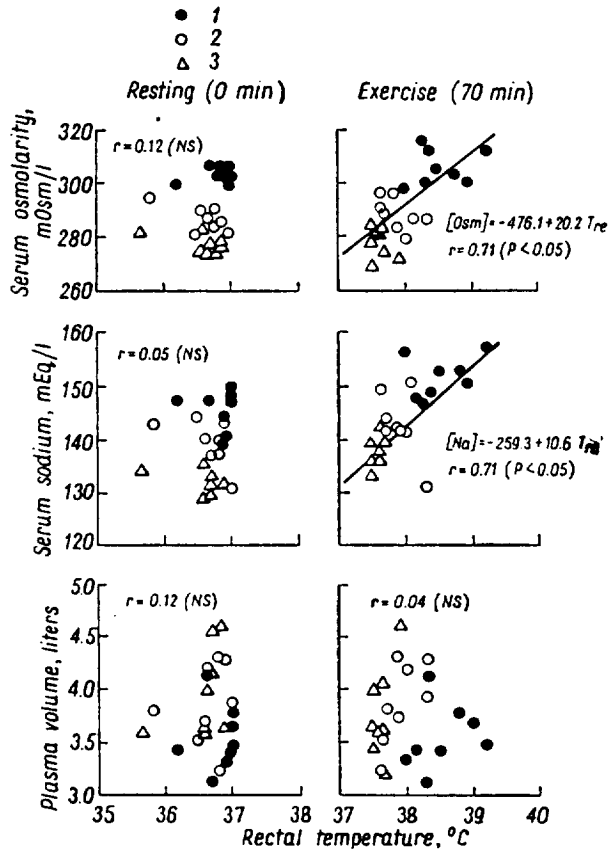


*Fig. 2.* Regression of serum osmolarity, serum sodium, and plasma volume with rectal temperature at rest and at the end of exercise under three hydration regimes. N. S. means not significant at the $p < 0.05$ level. *1* — Hypohydration; *2* — Normal hydration; *3* — Hyperhydration.

The highest correlations between mean body and rectal temperatures were with serum osmolarity and serum sodium; individual values for these variables plus plasma volume are plotted in Figure 2. At rest there were very low, nonsignificant correlations between osmolarity, sodium, plasma volume, and $T_{re}$ (Fig. 2 left half). However, at the end of exercise there were significant correlations between $T_{re}$ and osmolarity ($r = 0.71$) and $T_{re}$ and sodium ($r = 0.71$) while the correlation with plasma volume was very low ($r = 0.04$). These results suggest an ion-osmotic mechanism important for temperature regulation rather than a volume mechanism.

This experimental design does not allow for separation of a specific sodium ion effect from a more general osmotic effect.

Mean body temperatures calculated from changes in sweating (Table 4) agree within 0.1°C with measured $\Delta\Delta\bar{T}_{mb}$ values, but show poorer agreement with equilibrium levels of rectal temperatures ($\Delta T_{mb70}$). Conversely, net metabolic heat production agreed within 0.1°C with $\Delta\bar{T}_{mb70}$ but showed poorer agreement with $\Delta\Delta\bar{T}_{mb}$.

## DISCUSSION

The important finding from this study was the significant positive relationship between rectal and mean body temperatures and serum sodium and osmotic concentrations when body temperatures was increased by exercise. The highest correlations were obtained at the of exercise when body temperatures had reached equilibrium and change in heat storage was minimal as opposed to the data obtained at 35 minutes where equilibrium conditions were not attained.

*Body temperature at rest.* Under the three hydration regimes there was a clear separation in rectal temperatures and the hypohydration rectal temperature was elevated ($p < 0.05$) at rest. Increased core temperatures, not caused by impairment of sweating, have been reported in resting men on restricted fluid intake [28] and after intravenous injection of NaCl [12]. An elevated body temperature is due either to a net increase in heat production or to a net decrease in heat dissipation. At rest, the average oxygen uptake with hypohydration was 0.37 liters/min, slightly lower than in the other two hydration levels, so the higher resting rectal temperature with hypohydratiom was not due to increased heat production. Decreased heat loss could occur by a reduction in radiation, conduction, convection, or evaporation. Since the environmental parameters were essentially constant for all experiments, changes in ambient radiation, conduction, and convection were of minimal importance. Thus, variations in the rate of respiratory and dermal insensible heat loss probably accounted for the reducted heat loss. Respiratory and insensible heat losses were not measured at rest, so this possibility remains unresolved. One other possible mechanism is that the hypothalamic setpoint was re-set at a higher level, permitting greater heat storage and higher core temperatures, by the increased serum sodium concentrations [30, 31, 32]. *Myers* and *Yaksh* [32] found core temperatures elevated 2° to 3°C in restrained monkeys by increasing the ratio of sodium to calcium in fluid perfused into the cerebral ventricles. They hypothesized that the ratio of $Na^+$ to $Ca^{2+}$ within the posterior hypothalamus may be the mechanism for controlling the thermoregulatory setpoint. In the present study, at rest, there

were extremely low correlations between serum sodium and osmolarity and rectal temperature, so the elevated $T_{re}$ with hypohydration is not due to increased ionic concentrations as measured in peripheral blood. Higher ionic concentrations may have an effect on body temperature. In resting animals, it has been observed that injection of sodium chloride has no effect on temperature regulation [8, 24], but there is sufficient evidence to the contrary to warrant further research [1, 12, 15, 26].

*Body temperature during exercise.* In the present study the high correlations between serum sodium and osmotic concentrations with equilibrium levels of rectal and mean body temperatures suggest that ionic mechanisms are important for body temperature control in man. Injection of ions directly into the animal brain is an artificial process. The major question, therefore, is whether the relationship between osmolarity and sodium concentration in peripheral blood and body temperature levels is the result of ionic action at the hypothalamus, of ionic action on the peripheral mechanisms of heat dissipation (sweating and peripheral blood flow), or both. A change in the hypothalamic setpoint by ion changes could directly influence sweating and peripheral blood flow via the nervous system. *Senay* [38] found that the decreased rate of evaporative weight loss in men resting and working in the heat was significantly correlated with the increase in serum sodium concentration which he attributed to a direct action of sodium on sweat gland function, i.e., a decrease in secretion, an increased water reabsorptive capacity, or both.

In the present study, there are several possible explanations for the elevated rectal temperatures during exercise in the presence of greater water deficits. Respiratory heat loss during the three hydration regimes was essentially constant — it varied from 20 to 22 kcal/($m^2 \cdot hr$); tissue conductance (peripheral blood flow) also was constant (Table 2), so these two variables can be eliminated as causes for reduced heat dissipation. Since metabolic heat production is a function of absolute work load, and each subject worked at a constant load under each hydration regimen, the progressive increase in oxygen uptake from hyperhydration to hypohydration was due either to a systematic increase in the work load (which seems unlikely because the experiments were conducted in random order) or to the level of hydration. The higher heart rates with increasing dehydration may be compensation for a reduced stroke volume resulting, in part, from the lower plasma volume [33]. The increased work of the heart may have accounted for part of the increased oxygen uptake with dehydration. Another possible contributory factor for the increased oxygen uptake is that dehydrated subjects often are more irritable and less relaxed than when fully hydrated and any increased irritability may have contributed to the greater oxygen consumption.

At equilibrium, skin temperatures were the same for the three hydration levels while rectal temperature was progressively higher and total sweat rate progressively decreased with increasing levels of dehydration. Thus, total sweating was not related directly to skin temperature or to rectal temperature. Our calculations suggest that the progressively higher core temperatures were due to the sweating deficits; i.e., core temperature is not the main variable being controlled but its equilibrium level is the result of sweating deficits and sweating is the controlled variable.

It has been difficult to show a direct influence of intravenous saline injections on thermoregulatory responses in resting animals and man, but the clear positive relationships between increased serum sodium concentrations and elevated body temperature with exercise with constant respiratory water loss and tissue conductance imply that hypernatremia may be important for the control of sweating. Results from the present study do not differentiate the action of the sodium from the total osmotic concentration. The high correlations between body temperatures and osmolarity could have been due to the large contribution (70 to 80%) sodium makes to total serum osmolarity. At rest, the site of the action of sodium in animals appears to be on the posterior hypothalamic temperature centers [32]; but during dehydration from ambient heat in man the ionic stimulus could affect sweat gland discharge by triggering nervous impulses from the central nervous system, by the presumably increased osmolarity of the interstitial fluid surrounding the sweat glands, or by both mechanisms.

During exercise in dehydrated men, the degree to which the increased sodium concentrations in peripheral blood reflect increased intracerebral sodium concentration has not been established; i.e., can electrolytes penatrate the blood-brain barrier or are ony fluid shifts involved? It has been known for some time that the anterior hypothalamic-preoptic area contains osmoreceptors sensitive to osmotic changes in peripheral blood [25]. The osmoreceptor zone is localized in the immediate area of the supraoptic nucleus, and about haft the osmosensitive cells respond to hypertonic sodium chloride solutions as opposed to other sensory stimuli [23]. Recent evidence by *Rapoport* et al. [37] indicates that the blood--brain barrier can be opened to the passage of albumin from osmotically shrinking barrier cells by various salts, such as LiCl, $Na_2SO_4$, and NaCl, that have little or no lipid solubility. So it appears sodium and other electrolytes in peripheral blood can penetrate the blood-brain barrier. An alternative hypothesis is that osmotic substances may act as „gate-keepers" for the selective penetration of larger molecules that are active in temperature regulation; e.g., the prostaglandins. Sodium could perform

a double role as „gate-keeper" from its osmotic action and a trigger function due to its specific ionic properties.

Cerebral temperature is determined mainly by cerebral arterial blood temperature and blood flow [22]. During exercise, average blood flow through the brain is increased only slightly, if at all, but there is a large increase in blood flow in some areas and decreased flow in other areas with a moderate increase in cerebral blood pressure [36]. Although peripheral vessels in the head do not constrict, it may be that local osmotic changes in the hypothalamus could alter hypothalamic blood flow and hypothalamic temperature. The statistical relationships between serum sodium and serum osmolarity and core temperature from the present study do not provide conclusive proof of cause and effect, but simultaneous measurements of ionic concentrations in the temperature-regulating centers and in peripheral blood would answer this question.

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Authors' address: Dr. John E. Greenleaf, 239-17 NASA-Ames Research Center Moffett Field, California 94035.